ON HEMISECTION

OF

THE SPINAL CORD.

BY

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Reprinted from " Brain," *Winter Part,* 1891.

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Some doubt has been recently[1] thrown upon the method of transmission of sensory impressions by the spinal cord, long ago enunciated by Brown-Séquard.[2] The conclusion, that all sensory fibres, with the exception of those subserving the muscular sense, decussated and passed up the opposite side, immediately or shortly after their entrance into the cord, was based on the records of clinical cases and on experiments made on guinea-pigs. Our intention here is to pass in review the whole series of recorded cases of "Brown-Séquard's paralysis" amounting to nearly 60 and to add a series of original experiments on monkeys, undertaken with the two-fold object; (1) to explain, if possible, the apparent discrepancies between the results obtained by the earlier observers and those more recently recorded; and (2) to ascertain the duration of the symptoms which might primarily result from hemisection of the spinal cord;—a point of very great importance in connection with the question of restitution of function.

The experiments were performed in the Neuro-Pathological laboratory of King's College. The facts of experiment here recorded were for the most part verified by Professor Ferrier.

1. Clinical.

It has been found necessary at the outset to divide the recorded cases of this paralysis into two great divisions: (1) those which were observed and recorded immediately

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[1] Dr. F. W. Mott, Proc. Physiol. Soc., January, 1891.
[2] Brown-Séquard, Journal de la Physiologie, vol. vi., and Lancet ii., 1868.

after, or within a short time of the injury or onset of the
disease; (2) Those which were not carefully observed until
months or years after the onset of the symptoms. That
this division has been rendered essential will be seen from
what follows, but the statement may be made now, that
the presence of a set of symptoms at any given time is no
evidence of their existence either a short time previous or
later on; a constant tendency to the restitution of the func-
tions of the injured portion of the spinal cord occurring in
those parts which remain intact.

1. *Cases which were observed immediately after or within
a short time of the onset of the symptoms.*[1]

Tactile sensibility.—In all the cases, which have been
collected, the sense of touch was present on the paralysed
side. In the great majority there was hyperæsthesia of this
as well as of the other forms of sensation; in several it is
simply stated that all forms of sensation were preserved;
but in three (Nos. 9 and 22[2]) it is definitely noted that the
sensibility to touch was normal, while pain and temperature
were augmented. In the major number of the cases this
state obtained both in the paralysed leg, as well as in the
paralysed arm, when the lesion was situated in the upper
cervical region. On the non-paralysed side or side opposite
to the lesion one finds that in the greater number there is
complete anæsthesia of all forms of sensation; in a few the
sensibility is defective; in No. 39 (Gowers' case) there was no
loss of tactile sensibility and only incomplete analgesia. In
No. 42 although there was analgesia, the sensibility to touch
was merely lessened; In 13, 55 and 56 tactile sensibility
was only defective, while in 44 it was retained. In No.
52, the paralysed leg presented a hyperæsthesic condition,
while the paralysed arm showed "loss of feeling"; the non-
paralysed leg was anæsthetic, the corresponding arm being
normal as regards both motion and sensation.

Sensibility to pain (pricking and pinching).—What has
been said with regard to touch, holds good for pain on the

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[1] Cases of tumor of the spinal cord have, for obvious reasons, been left out
of the collection.

[2] The numbers refer to the list of cases at the end of the paper.

paralysed side. As a rule there is hyperæsthesia of painful impressions. In No. 9, pain and temperature impressions were augmented, while touch was normal : in No. 14, pain only was increased. On the side opposite the lesion there is analgesia ; in No. 13, there was analgesia and thermoanæsthesia, the sense of touch being only diminished: in No. 39, there was defective sense of pain without any affection of tactile sensibility ; and in No. 56 with defective sense of touch and pain, there was loss of the sense of temperature. In No. 30, there was blunting of the sensibilities of pain and heat, the sense of touch being unaffected.

Temperature sense.—This behaves in most cases as the other forms of sensibility, *i.e.*, increased on the paralysed side, and lost or diminished on the side opposite the lesion. But amongst the recorded cases there are several well-marked instances where this form of sensibility dissociated itself from the others. In Nos. 55 and 56 there was thermoanæsthesia on the non-paralysed side, existing with defective pain and tactile sensibilities. No. 55 is especially important, for the patient was seen two and a half years later, and although the other forms had to some extent been restored, there was still complete loss of temperature sense on the side opposite the lesion.

The sense of localisation.—Brown-Séquard's conception was that there existed perfect knowledge of the localisation of impressions on the paralysed and hyperæsthetic limb, while there was loss or great diminution of this faculty on the anæsthetic side. The collected cases appear to corroborate this view.

The muscular sense.—On this point there is more diversity of opinion, than on any one of those previously considered. Brown-Séquard believed that this sense (the sense of detecting difference of weights, or of telling the position of the limbs without the aid of sight) was in abeyance on the paralysed side; but Dr. Ferrier (BRAIN, vol. 7, p. 1) showed, as a result of hemisection of the spinal cord of a monkey, that the sense of position of the limb appeared absent, not on the paralysed but on the opposite side (viz. that on which there was cutaneous anæsthesia). In several

of the collected cases no mention is made of this condition, while in others the only tests employed were those of "directing movements" or "perceiving strong pressure." It is therefore necessary, when noting the presence or absence of the muscular sense, to observe the sensibility of the skin to tactile impressions. In Nos. 11, 13, 15, 21 and 57, the muscular sense was present on the apparently anæsthetic side, but on this side there was no loss of tactile sensibility. In Nos. 26 and 45 it was lost on the anæsthetic side, in the latter it is especially stated that the patient was unable to tell when the eyes were closed, the position of the toes, foot, or lower part of the leg, over which parts there was complete tactile anæsthesia. There was some uncertainty of the muscular sense on the paretic side in No. 54, but here the tactile sensibility was defective.

2. *The cases which were observed months or years after the onset of the symptoms.*

In a case recorded 3 months after the onset of the symptoms (No. 48) there was paralysis on the side of the lesion ; and on the opposite side, defective sensibility to touch and tickling, with analgesia and thermoanæsthesia. In several seen six months after, both the amount of paralysis and the condition of the sensibility varied. In No. 40 there was on one side paresis with normal sensibility, and on the other anæsthesia of all forms of sensation. In No. 49, on the opposite side the sense of contact was defective, while that of pain and temperature were entirely lost. In No. 50 a weakness in the finer movements summed up the motor defect, while pain and temperature sensibilities were in complete abeyance on the opposite side. In No. 52, with paresis of arm and leg on one side, there was on the opposite side defective sensibility in the leg, while the arm was normal. In one seen twelve months after onset (No. 45) there existed paresis of one side with defective sensibilities on the other. In No. 55, which was seen two and a half years after the first observation, all forms of sensibility had returned in the leg with the exception of pain and temperature. No. 16 was seen three years after the onset and slight hyperæsthesia still existed on the paralysed side, and on

the opposite side, although touch was present, there was analgesia. In two of Brown-Séquard's cases (Nos. 3 and 20) observed eleven and twenty-one years after a stab in the back, and a fall off a staircase respectively, hyperæsthesia existed on the paralysed side, which was also rigid, and on the other side all forms of sensation were abolished except tactile sensibility which was defective. On the other hand in a case seen twelve years after a similar injury (No. 53) on one side there was defective movement with normal sensibility, on the other touch, pain and temperature senses were only diminished.

It is necessary further to study with some detail those cases in which the lesion was situated in the cervical region of the spinal cord. Of the sixty collected cases, specific mention is made of the arms and legs in seventeen. Of these, thirteen show the usual appearance of "Brown-Séquard's paralysis" in both upper and lower limbs; the remaining four are of great interest when taken in conjunction with the experiments on monkeys shortly to be detailed. In case No. 3 (Brown-Séquard), as a result of a stab high up in the neck, a patient developed paralysis of the right arm and leg. On the paralysed leg there was hyperæsthesia of all forms of sensation, while on the non-paralysed there was defective tactile sensibility, analgesia and thermo-anæsthesia. On the right or paralysed hand, the two points of the æsthesiometer were recognised at 2-3 c.m.; and although the upper arm was anæsthetic, the senses of tickling, pain and temperature were exaggerated. On the non-paralysed arm there was more or less anæsthesia to all forms. In No. 5 (Perroud, quoted by Brown-Séquard) the "sense of contact" is stated to be diminished on the paralysed forearm, but no mention is made of the sensibility of the other arm. In No. 7 (Brown-Séquard), paralysis of the right arm and leg resulted from a stab in the neck. In the lower limbs there obtained paralysis with hyperæsthesia on one side, anæsthesia on the opposite side, while there was incomplete anæsthesia on both arms. Lastly in case 52 (Hoffman) the following condition was observed: Paralysis of the right leg with hyperæsthesia, paresis of the right arm with "loss

of feeling"; anæsthesia of the right leg, while in the left arm "motion and sensation were good."

Among other facts in connection with the collected cases may be mentioned :—The organic functions are as a rule disturbed for a short period after the injury to the spinal cord, in the majority of cases incontinence of urine and fæces lasted from ten days to a fortnight. In a few cases constipation was present. The bilaterally associated movements of respiration are not affected, the two sides of the chest moving equally immediately after the lesion : In No. 52 paresis of the diaphragm on the side of the motor paralysis was noted, while in Nos. 46 and 54 special note is made of the fact that the abdominal muscles on the side of the lesion were paralysed. The condition of the reflexes calls for special mention. In nearly all the earlier cases recorded by Brown-Séquard and others, the superficial reflexes, especially the plantar, were observed to be augmented on the non-paralysed side, while in the later cases the condition of the knee jerk was noted. Immediately after the injury the knee jerk is absent or diminished on the paralysed side and normal on the opposite side. During the progress of the case, it returns and in course of time becomes somewhat exaggerated.

Before leaving the discussion of the recorded cases of this paralysis, it should be noted that only in a very few instances a *post-mortem* examination was obtained.[1]

It is, therefore, impossible to say whether in the majority of cases the lesion was a truly unilateral one or not. But arguing from the facts of experiments it appears probable that the major portion were of this one-sided character.

2. *Experimental.*

Before detailing the experiments, the methods of operation will be mentioned. Monkeys were used in every case, and the operation itself was regarded as a surgical procedure under strictly antiseptic precautions ; in all cases the wound healed by the first intention. Chloro-

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[1] These are Nos. 24, 25, 27, 29, 39, and 46.

form was the anæsthetic employed. The vertebral spines and laminæ were exposed in the usual way, and the canal opened into with the bone forceps. The theca was incised mesially, and at either end of this incision two oblique cuts were made outwards, so as to expose the entrance of the posterior nerve roots on either side. The posterior median fissure is usually obscured by a blood-vessel. This having been moved to one or other side, a grooved transfixion knife was passed through the cord in the middle line of the body, and one-half of the cord severed. The wound was then closed.

Experiments on animals made with a view to investigate conditions of sensation are beset with fallacies, and the symptoms may be differently interpreted. We have, therefore, in detailing the experiments, noted what we saw. The two chief difficulties which stand in the way of this method are—(1) Complications arising from reflex action. It is pointed out that this is excessive in the lower limb on the side opposite the lesion ; in some of the cases a drop of water or a breath of cold air on the non-paralysed foot setting up active movements of the leg. (2) As one can only infer the presence of sensation by the movements which occur, it is possible sensation may exist not evidenced by movements. In a few of the cases on the day following the operation, it was difficult to ascertain definitely the presence of a sense of touch owing to slight apathy, but after the first twenty-four or thirty hours the animal assumed its normal state.

EXPERIMENT 1.—*A section of the right side of the spinal cord at the level of the ninth dorsal nerve root* was made on April 11th, 1891. A well-conditioned male Rhœsus monkey was used. On the day following the operation, which is regarded as the *first* day of observation, and when all appearance of shock had passed off, the following condition was noted :—There was complete paralysis of the right lower limb, while the left, although it was freely moved when the animal lay upon its back or tried to escape, was not used for prehension when climbing the lattice-work of the cage. Its attention was at once arrested by ruffling the hair, pricking, pinching, and the application of a dull hot

wire to the skin of the right lower limb, while it paid absolutely no heed to any of these forms of stimulation on the left. There was no reason to suppose from the manner in which it responded to the various forms of irritation that they were felt more keenly than normal. The right foot felt warmer than the left, while a surface thermometer recorded on the sole a difference of 16° F. between the two (right sole 86° F., left sole 70° F.). The right knee-jerk was not obtained, while the left was more marked than normal. The superficial reflexes, especially the plantar, were much more active on the left or non-paralysed limb. This condition remained until the *third day*, when, on touching the region of the left knee with the hot wire, the monkey would bring down its hand and scratch, but never struggle or show signs of discomfort. On the *fifth day* when pricked with a pin about the left knee, but much more evident when the hot wire was applied to the limb generally, it brought its hand down to the place touched and localised it. It took no notice of ruffling the hair on this side. The reaction to cutaneous irritation of the right side remained as before. On the *tenth day* the physical signs corresponded to those in the last note ; it was evident that painful impressions were perceived, but much less readily than on the right limb. By the *twenty-fourth day* the power of flexing the right hip joint had returned. For the first time, the "clamp test" (Schiff) was introduced into the routine of testing, and this revealed interesting facts not altogether easy of interpretation. It was noted that when the clamp was applied to the right leg, struggling and other signs of discomfort immediately ensued, but there was no attempt to remove it, while if it was applied to the left leg, there was no sign of discomfort, but the leg was at once drawn up and the clamp was pulled off. It seemed as if the cause of this was the excessive reflex action of the non-paralysed side ; to overcome this the legs were held, and the clamp again applied to the right leg ; at once the struggling commenced, and continued until the clamp was withdrawn, while the monkey took absolutely no notice as long as the clamp was attached to the left side. On freeing the legs, however, the left was

drawn up and the clamp pulled off. The temperature of the soles was the same. This doubtful condition remained for some days, but on the *thirty-eighth day* the following state was noted :—There is considerable return of the movements of the right leg, flexion and extension at the hip and knee joints being well effected. The left leg is now used much more extensively than before. The animal takes no notice of the pinching with forceps on the left side, but brings its hand down in an indefinite way when pricked gently at the root of the tail and the lower part of the back, and an equal degree of pricking causes more discomfort on the right than on the left side. When the animal's attention is diverted, ruffling the hair by blowing through a long glass tube invariably causes it to scratch. It does not take so much notice of the dull hot wire on the left as on the right side. The reactions to the clamp remain the same. On the *fifty-third day* the movements of the right leg had almost entirely returned, a slight drop-foot only indicating what had been a paralysed leg. There was also some wasting of the muscles of this limb. It took notice of pricking and pinching and ruffling the hair on the left leg as it did on the right. From this date onwards it was impossible to say which had been the anæsthetic limb; it responded as readily to all forms of stimulation on the one side as on the other.

On the *sixty-eighth day* (June 23rd, 1891) after the section of the right side of the cord, *a section of the left side at the level of the sixth dorsal nerve root was made.* The result of this was complete paralysis of both lower limbs, and complete anæsthesia of both limbs. It paid no attention to any forms of stimulation when applied to the legs, but readily when applied to the arms. The superficial reflexes on the right side now became markedly exaggerated. From this date onwards to the *one hundred and thirteenth day* after the original operation, when it was killed under an anæsthetic, the monkey showed no signs of returning motion or sensation. Both lower limbs became contracted and rigid and atrophied, the knee-jerks were active, the right remaining more marked than the left, and the superficial reflexes were also active.

Pathological examination.—At the seat of both incisions the dura mater was adherent to the surrounding bone, the membrane itself being slightly thickened. The spinal cord was removed and hardened in Müller's fluid. After some weeks, sections were made at the seat of both lesions, and double-stained with the Weigert-Pal and Carmine (Upson's) methods. In the first lesion, at the level of the ninth dorsal nerve, the following features were observed:—The incision was filled in by a layer of white fibrous tissue, which extended from the periphery to the line of the central canal. The whole of the right side of the cord had been destroyed, but in addition a small portion of the left postero-median
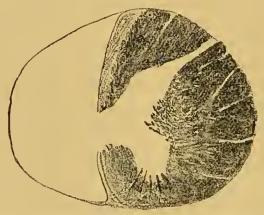

Fig. 1. (Exp. 1.) Representation of a section made through the lesion at the level of the ninth dorsal nerve roots. The unshaded portion of the section is the right side of the spinal cord. The anterior and posterior median septa are represented. The degeneration of the white matter on the left side of the cord is probably of " traumatic " origin.

column. The central grey matter on the left side maintained its normal shape, but its structure appeared slightly altered, owing probably to a certain amount of " traumatic degeneration," which had also increased the neuroglia of the white matter lying in close relation to it. At the sixth dorsal root, where the second hemisection was made, the right half of the spinal cord was intact, with the exception of the ascending degeneration, resulting from the lower lesion. The incision had not been filled in with new tissue, but remnants of very much degenerated cord substance were found in front and behind.

EXPERIMENT 2.—*Section of the spinal cord on the left*

side at the level of the seventh dorsal nerve root was made in a female Rhœsus monkey, June 10th, 1891. The animal recovered very rapidly from the operation, and presented the following features :—Complete paralysis and flaccidity of the left lower extremity, while the right was moved well in all directions ; although, as occurred in the first experiment, the non-paralysed leg was not used for any useful purpose, as, for instance, when it was climbing the lattice-work of the cage. This was, no doubt, due to the fact that owing to the cutaneous anæsthesia, the sense of the position of the limb was lost, and, without the aid of vision, it did not know where its right leg was. When the skin of the left leg was tickled, scraped with a blunt instrument, or gently pricked and pinched, its hand was at once brought down accurately to the place which was irritated. Absolutely no notice was taken of any of those forms of irritation when applied to the right lower limb. The superficial reflexes on the right side were markedly exaggerated. The paralysed limb further communicated a feeling of greater warmth to the hand than the non-paralysed. By the *sixth day* the monkey localised correctly the places on the right leg where it was pricked, or when the skin was tickled by blowing upon it, but it never struggled or showed signs of discomfort. Similar reactions to the clamp test ensued in this case to those observed in the first experiment. When the clamp was applied to the left side, the animal invariably struggled, and appeared annoyed by the presence of the clamp, but never tried to remove it. On the right leg, however, it never showed the slightest sign of any discomfort, even when the clamp was kept applied for several minutes ; it was only necessary to free the limb which was being held, when the leg was drawn up and the clamp removed.

During the succeeding weeks, when the animal was under observation, the responses to the tests showed little or no variation from what is stated above. All forms of irritation, including the clamp test, arrested its attention when applied to the left leg ; on the right leg, however, although pricking, pinching, and the hot wire usually attracted notice, the response was obtuse, and a greater

severity of stimulation was required.   Return of movement
was first noticed at the left hip-joint on the *twenty-second
day*, and this proceeded until between the *fiftieth and sixtieth
days* when movements had entirely returned, with the persis-
tence, however, of slight drop-foot.   The monkey was killed
upon the one hundred and twenty-seventh day after the
operation.

At the *autopsy*, the hemisection was found to be at the
level of the seventh dorsal nerve root.   After hardening the
cord for some weeks in Müller's fluid, sections were cut and
stained by the Weigert-Pal method.   Sections made at the
level of the lesion showed that the whole of the left half of
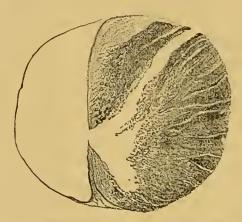the cord had been destroyed, and to some extent also the

FIG.   2.   (Exp. 2.)   Section through the lesion at the level of the seventh
        dorsal nerve roots.   The unshaded portion of the figure represents the
        left side of the spinal cord.   The degeneration on the right side of the
        middle line is probably of " traumatic " nature.

anterior and posterior median columns on the right side.
The space intervening between the cut ends of the left side
of the cord was filled with white fibrous tissue, in which
there was no evidence of regenerating nerve fibres.

These two experiments may be regarded as presenting the
characteristic features of hemisection of the spinal cord in
the mid-dorsal region.   For a few days after the infliction of
the injury, *all forms of sensation are lost on the side opposite
the lesion*, while on the paralysed side all forms are pre-
served.   After three to six days sensibility begins to return
on the anæsthetic side.   The first experiment showed that

the order of return was sense of pain (heat) on the third day, sense of pain (pricking and pinching) on the fifth, while in the second all forms, pain (heat), pain (pricking and pinching) and touch had returned simultaneously by the sixth day. There exists some doubt concerning the late return of the sense of touch in the first experiment. Our notes indicate that for many days much dubiety existed regarding the sensibility of the non-paralysed leg, so that it is not improbable that the sense of touch returned considerably earlier than is noted here. A certain obtuseness of sensibility obtains for some time after its restitution ; the monkey withstands severe forms of irritation on the side opposite the lesion.

In both the experiments, movement at the hip-joint on the paralysed side was observed between the twentieth and the twenty-fourth days ; at the knee-joint between the thirtieth and fortieth days ; while dorsiflexion of the ankle remained in abeyance for a long time.

EXPERIMENT 3.—*A section of the left side of the spinal cord of a male bonnet monkey* was made between *the third and fourth cervical nerves* on May 26th, 1891. On the day following the operation one observed, that there was complete paralysis of the left arm and leg; as regards the sensation, (1) of the lower limbs ; the animal paid no attention when it was touched on either leg, but it was dull and apathetic ; it however readily responded by bringing its hand down to the place when it was pricked, pinched or touched with a dull hot wire on the left leg. No such response was evoked when the right lower limb was similarly irritated. (2) Of the arms; all forms of irritation except ruffling the hair at once arrested its attention when applied to the right upper limb; but there was considerable difficulty in determining the exact condition of the left. It took no notice of ruffling the hair by blowing through a glass tube or of gently scraping the surface of the skin with a blunt instrument, while it would struggle slightly or open its eyes when this limb was pinched, pricked or touched with a hot wire. Owing to its apathetic state it was difficult to estimate the sensibility to touch on the extremities; the sensibility to pain and heat

resolved itself as follows: analgesia of the non-paralysed leg, obtuseness of sensibility on the paralysed arm, while the paralysed leg and the non-paralysed arm presented normal reactions; there was no reason to suspect that there was any hyperæsthesia on these limbs. Tickling the sole of the right foot occasioned a lively reflex drawing up of the leg. The temperature of the left sole was 5° F. higher than the right. The right arm and leg were freely moved.

On the *seventh* day there was no sign of any return of movement in either limb on the left side, but when the hair on the right buttock and thigh was gently pulled or the skin lightly scraped or pricked, the animal at once brought down its right hand and scratched the place which was irritated. It was several times seen to spontaneously scratch the right thigh. And further, pricking the right foot and leg caused it to move away or, if held, to struggle. The same notice was taken when the left arm was pricked, but to a much less extent and the prick required to be more forcible. It was able to climb the lattice work entirely by means of its right arm and leg. On the *thirteenth* day, the first return of movement was noticed—flexion at the left hip joint; it responded to all forms of irritation (touch, pain, heat) on the left leg and the right arm and the right leg; much difficulty was experienced in ascertaining the sensibility of the left arm; the monkey was never aroused from its occupation when the arm was touched, but when pricked or when the hair was pulled it looked up but did not show signs of discomfort. On the *twenty-ninth* day the movements of the left leg were well marked at the hip and knee joints; the monkey readily took notice of all forms of stimulation on the legs. As in the first experiment the clamp was removed from the right leg, but never from the left. It was still difficult to determine the tactile sensibility of the left arm, it responded to painful impressions, but less readily than on the right side. By the *fifty-fifth* day some power of movement over the shoulder joint had been regained, while the increase in motor power of the left leg had advanced. There seemed to be no doubt that touching the left arm and hand or very gently pulling the hairs were felt, because the animal

invariably looked round and moved away, when this was done. Its perception of tactile impressions on this limb was distinctly blunted, as also was its perception of painful impressions. On the *one hundred and sixth day* the note was made that there was almost complete return of the movements of the left leg; the left arm was still paretic; it could not raise the elbow higher than the shoulder and there was marked wrist-drop. The sensibility remained the same as at the last note. The monkey died on the one hundred and twenty-sixth day after the operation.

Pathological examination.—Owing to a considerable amount of adhesion between the spinal cord, dura mater and
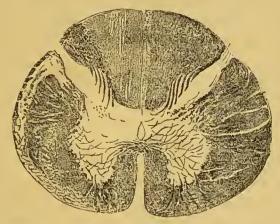

Fig. 3. (Exp. 3.) Transverse section of the spinal cord at the level of the second cervical nerve root, showing ascending degenerations following a section of the left side of the cord between the third and fourth cervical nerves.

vertebral column in the upper cervical region, some difficulty was experienced in removing the cord, with the result that the latter was torn at the seat of the lesion, so that we are unable to figure the exact amount of destruction of the cord. Careful examination has been made of the ascending and descending degenerations. The tracts which degenerate upwards are, on the left side, the whole of Goll's column, the direct cerebellar tract, and the ascending antero-lateral tract of Gowers. On the right side of the posterior median fissure there is a small linear area of degeneration in the postero-median column. The descending degenerations are the crossed and direct pyramidal tracts on the left side, and

a small portion of the direct pyramidal tract on the right side. The lesion itself was situated between the third and fourth cervical nerves on the left side.
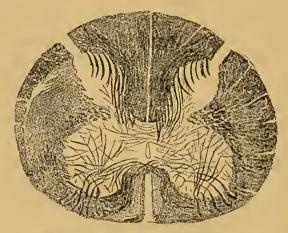

FIG. 4. (Exp. 3.) Transverse section of the spinal cord at the level of the seventh cervical nerve, showing degenerations descending from a section of the left side between the third and fourth cervical nerves.

EXPERIMENT 4.—*A section of the left side of the spinal cord at the level of the third cervical nerve* was made on Nov. 3rd, 1891. A large male Rhœsus monkey was used. On the day after the operation the state of motion and sensation was as follows : The left arm and leg were completely paralysed, while the right were freely moved at all the joints. All forms of cutaneous irritation applied to the left leg, buttock and flank (gently ruffling the hair, scraping the surface of the skin, pulling the hair, pricking, pinching, and the dull hot wire) at once arrested the animal's attention. When the clamp was applied to the sole of the left foot or to the skin of the leg, struggling at once ensued, but there was never any attempt to remove it, and this continued as long as the clamp remained attached. Absolutely no notice was taken of any of these forms of irritation on the right leg, buttock or flank, but when the clamp was attached to the right sole, the leg (unless held) was speedily drawn up and the clamp pulled off. Pricking, pinching, and the clamp forceps gave rise only to slight signs of discomfort when applied to the right upper limb, while the monkey struggled considerably when the left arm was pricked or pinched or touched with

the hot wire.   It paid no heed to gently scraping the skin or ruffling the hair of this limb, although its attention was at once arrested when a drop of water was allowed to fall upon either hand.   It struggled when the clamp was applied to both hands, but less on the right than on the left side.   It never tried to remove the forceps from the left hand.   The right knee jerk was well marked, the left was present but feeble.   The superficial reflexes on the right side were very active.

On the *second* day the monkey again removed the clamp from the right sole, but there was no evidence of any discomfort when it was applied.   It never attempted to remove the clamp from the left sole, although it struggled as long as the pressure of the clamp was kept up.   In all other respects, it remained as on the previous day.

On the *fourth* day, the reactions were as at the previous observations, but with this addition that pricking the right leg or right root of the tail would occasion a slight amount of struggling, as if there were some, but defective, perception of painful impressions.

On the *fifth* day the monkey died.

The autopsy revealed a hemisection of the spinal cord at the level of the third cervical nerve.

EXPERIMENT 5.—*Section of the left side of the spinal cord at the level of the fourth cervical nerve.* (Made on Nov. 17th, 1891, in a male dog-faced monkey).

On the following day there was paralysis of the left leg and almost complete paralysis of the left arm, a slight movement at the shoulder joint being occasionally observed. Absolutely no notice was taken of any form of irritation applied to the right lower limb ; when the clamp forceps was applied to the sole of the foot or elsewhere on the leg, a sudden spasmodic movement ensued of probably reflex nature, but the clamp was never removed, nor was there any attempt at removal.   Similar forms of irritation on the left lower limb caused struggling and attempts to move away ; and on the application of the forceps evident signs of discomfort, but no endeavour to remove it.   The monkey bore, with only a small amount of struggling, pricking and

pinching the right upper limb, but at once responded to a touch either of a blunt instrument or of a drop of water let fall upon its hand. It at once took notice of pricking and pinching the left upper limb and also when the clamp was applied, but we were unable to detect at first any evidence of a sense of contact on this limb, as the monkey paid no attention to ruffling the hair or dropping water on its left hand. The superficial reflexes of the right lower limb were very marked, and the right knee jerk was readily obtained. The left knee jerk although present was feeble. The temperature of the right sole was 86° F, while the left was 94° F, that of the right palm was 84° F, while the left was 94° F. On the *second* day similar tests were employed, but no alteration was noted in the condition of sensation ; special attention was devoted to the tactile sensibility of the left hand, but no evidence of any recognition of tactile impression was obtained. On the *third* day, however, when the monkey was lying quietly before the fire, a drop of water let fall upon its left hand at once arrested its attention. The right leg remained completely anæsthetic to all forms of irritation. There was no sign of discomfort when the clamp was applied to the limb, nor was there any attempt to remove it. The right arm and left leg remained as before This condition was confirmed daily until the *eighth* day, when on applying the forceps to the left arm, the monkey brought round its right hand and tried to remove them, and, further, when water was dropped upon the left hand or when the arm was gently scraped, it looked towards its hand, and attempted to move away from the irritation. This was the first indication of something more than a mere feeling of contact on the paralysed arm. The right leg remained completely anæsthetic to all forms of irritation. There was some increase in the amount of movement noted on the first day, but the animal was yet unable to stand or sit up. On the *sixteenth day* the right leg remained completely anæsthetic to all stimulation, excepting that when pricked at the root of the tail on the right side, and when the skin of this region was blown upon, the monkey brought its hand round to the place and scratched it.

There was no attempt to remove the forceps from the right foot; although it could sit up, it was unable to progress. It at once responded when touched on the arms and the left leg: pricking the right arm caused less evidence of discomfort than when the left arm and leg were similarly irritated. On the *twentieth day* the condition remained as recorded in the last note.

The three experiments just recorded of hemisection in the upper cervical region present some variations in the amount of sensory disturbance. The condition obtained in the third experiment was opposed to previously recorded facts, and as the monkey was a troublesome one to test, the other two experiments (Nos. 4 and 5) were performed. These latter presented symptoms more in harmony with what occurred after hemisection in the dorsal region. On the arm opposite the lesion, the sense of pain was abolished or defective, but contact was retained. On the paralysed arm all forms of sensibility (pain and contact) were present, at any rate within a short time after the operation. These experiments also indicate variations in the duration of the symptoms and in the occurrence of restitution. In the third experiment sensibility had returned in the lower limb opposite the lesion by the seventh day after the operation. In the fourth experiment evidence of the return of painful sensibility was obtained on the fourth day. In the fifth experiment the lower limb opposite the lesion remained completely anæsthetic to all forms of irritation up till the sixteenth day. The sense of pain on the non-paralysed arm remained very defective.

The Sensory Disturbances.

These experiments confirm the theory, which was originally advanced by Brown-Séquard, that the sensory fibres decussate immediately after, or within a short distance of, their entrance into the spinal cord and pass up the opposite side, while the motor fibres pass down the same side of the cord. This, however, appears to be only true of the sensory fibres for the lower, or hinder extremities. As far as our experiments show, a modification of this arrangement is

necessary for the upper or fore-limbs. That complete de-
cussation of the sensory fibres from the arms occurs is
shown by the facts of cerebral hemianæsthesia, but at the pre-
sent time it appears doubtful where this crossing takes place.
It is evident from the experiments which have been re-
corded, that monkeys vary both in the amount of sensory
disturbance which follows hemisection and in the duration
of the symptoms before restitution occurs; and the recorded
cases in man of lesion in the upper cervical region show some
irregularity in the distribution of the sensory defects in
the arms. The facts of the experiments in the upper cervical
region show that all forms of sensibility were not abolished
on the non-paralysed arm; sensibility to painful impressions
was absent or defective, except in the third experiment, while
the sense of contact was retained. On the paralysed arm,
with retention of the sense of pain, evidence of tactile
sensibility was obtained within a short period of the opera-
tion. This would appear to indicate that the fibres sub-
serving tactile sensibility for the arms pass up both sides
of the cervical cord, while those subserving painful and
temperature sensibilities mainly pass up the opposite side.
On the other hand, the experiments indicate that all forms
of sensibility, with the exception of a sense of pressure in
some monkeys, notably in experiment 4, are abolished in the
lower limbs, temporarily at least, on the side opposite the
lesion. In this connection we will here refer to the existence
of a sense of pressure, more or less accurately localised, as
shown by the clamp test. When the clamp was applied to
the skin of the foot on the non-paralysed or anæsthetic side,
the leg was at once drawn up and the clamp removed, while
the monkey never exhibited any signs of discomfort. When,
on the other hand, the clamp was applied to the paralysed
foot, the animal at once began to struggle and bite, and
show signs of annoyance, which continued during the time
the clamp remained on, but it never tried to remove it. If,
however, the anæsthetic limb was held, the animal never
attempted to remove the clamp until the limb was set free
and its movements unrestrained. In the fifth experiment,
as long as the limb remained anæsthetic to all other forms

of stimulation, no attempt was ever made to remove the clamp forceps.

There is, perhaps, greater difficulty in determining the condition of the muscular sense in animals, the conclusions depending entirely on the interpretation of the observed facts. The following observations appear to indicate that there is loss of the sense of movement in the lower limb opposite the lesion. When the animal was lying on its back, it could freely move and kick with the anæsthetic limb, but this leg was never used for prehension, as, for instance, when it was climbing the lattice-work of the cage. If a finger or other object was inserted between the hallux and the toes, no attempt was made to grasp it. If, when the eyes were blindfolded, the leg was moved about, the monkey never offered any resistance. If by chance the leg was caught upon an obstacle lying upon the floor, it was quite incapable of extricating it. All this, however, changed when the cutaneous sensibility returned.

The Restitution of Function.

1. *The motor functions.*—The collected cases and the experiments detailed above show that the functions of the side of the spinal cord which has been injured are in course of time restored. It has been pointed out that the movements returned in the paralysed limbs at different periods after the operation. The first movement to return is flexion at the hip-joint, and this occurred from a fortnight to three weeks after the infliction of the injury. Closely associated with this is the counter-movement of extension, and a short time later movements at the knee-joints are regained. Drop-foot remains for a very long time, apparently, after some of the movements of the hallux and toes have returned. Return of the functions of the paralysed arm occur much later than in the paralysed leg. First, movement at the shoulder joint, followed a little later by flexion and extension at the elbow ; in the third experiment, drop-wrist and inability to move the thumb and fingers persisted one hundred and twenty days after the operation. It therefore comes to be a very important point to ascertain

how this restoration takes place.   Regeneration of the white
fibres of the spinal cord probably does not occur, at any
rate, in the higher mammals, although definite evidence on
this point is not yet forthcoming.   Eichhorst (*Virchow's
Archiv.*, 1874, p. 1) found new nerve elements in the scar tissue
resulting from section of the spinal cord in young dogs and
rabbits.   Our own observations do not confirm this, for the
cicatricial tissue which filled in the gap made by the knife
at the time of the operation in no case presented any
evidence of regenerating nerve fibres.   As no regeneration
took place at the seat of the lesion in the experiments under
discussion, the impressions were probably conveyed to the
parts below the lesion by the opening up of decussating
paths from the opposite uninjured side.   Experiments seem
to corroborate this view.   The first experiment demonstrated
that after the recovery of movement from a section of one
side of the cord, section of the opposite side a little higher
up caused permanent paralysis of both lower limbs.   And
two experiments performed by Rossolymo (*Neurol, Centralbl.*,
1887, p. 292) on guinea-pigs, entirely confirm this.   In one
experiment he performed a hemisection of the spinal cord
at the tenth dorsal nerve root; and when the paralysis of
the hind limb resulting from this had passed off, he made
on the same side another section just behind the decussation
of the pyramids.   This occasioned paralysis of the fore limb
on the same side, while the hind limb escaped.   In a second
experiment, after restoration of the movement resulting from
a hemisection in the lower dorsal region, he made a vertical
longitudinal incision throughout the lumbar enlargement,
with the result that the leg was a second time paralysed.
He had previously shown that such an incision produced no
paralytic effect on either limb.   Dr. Mott's experiments
(*Proc. of Physiol. Soc. in Journal of Physiology*, Jan., 1891)
on stimulating the motor cortex after recovery from the
paralysis of a hemisection confirm this, for he found that
excitation of the cortical area of the opposite leg evoked
movements in both legs.

2. *Sensory functions.*—The restoration of these functions
is a subject which has not as yet received very much atten-

tion.   In cases of "Brown-Séquard's paralysis" which have
been observed several months or years after the onset of the
symptoms, no very marked improvement is found to have
occurred in the sensory conditions: in one example seen
twenty one years after the fall which caused the paralysis,
all forms of sensation were abolished with the exception of
touch, which was very defective.   An analysis of the order
and date of return of the sensibilities in the monkeys, which
have been the subjects of our experiments, shows a condition
differing considerably from the recorded cases of disease or
injury in Man.   In three of the experiments evidence of the
return of the perception of painful impressions was obtained
by the fifth or seventh day after the operation.   The per-
ception of these impressions was at first very defective.   An
amount of pricking and heat which caused distinct mani-
festations of feeling on the paralysed limb, on the non-
paralysed only provoked a sense of slight discomfort; the
monkey scratched the place irritated, but never or rarely
struggled.   In the second and third experiments the per-
ception of tactile impressions returned contemporaneously
with that of pain.   It appears that in the monkey at any
rate, probably owing to the less highly organised state of
its spinal cord restitution of the sensory functions occurs
at a much earlier date after the infliction of an injury,
than obtains in the highly organised cord of man.

The Paths of Sensation.

Brown-Séquard's view of the existence of special con-
ductors for the diverse kinds of sensory impressions and of
different paths for their conduction in the cord, was based
on the facts of many of the cases previously alluded to, viz.,
that one kind of sensibility was preserved while another
was lost.   He concluded that the temperature sense was
probably conducted by the central grey matter, painful
impressions by the posterior and lateral parts of the grey
matter, while the tactile sense was conducted by the ante-
rior parts of the cord.   More recent observers have suggested
other paths for the conduction of sensory impressions.
Schiff suggested that tactile sensibility probably passed by

the posterior columns, painful impressions being conveyed by the grey matter, while Dr. Gowers has advocated the antero-lateral ascending tract as a probable path of painful sensations.   Experiments have been performed recently which do not corroborate these views.[1]   Section of the outer portion of the lateral column in a monkey produced no effect upon sensibility below the lesion, while section of the whole of one side of the spinal cord, with the exception of the anterior and posterior median columns, gave rise to total anæsthesia and analgesia on the opposite side.   The experiments tend to show that all forms of sensation pass up the cord in very close relation to each other, and their synchronous restoration after hemisection would favour this view. It has been suggested, because the ascending degenerations which follow hemisection are limited to the same side of the cord, that therefore the sensory fibres do not entirely decussate.   It is true that anatomically the ascending degenerations are limited to the same side as the lesion, but clinically the anæsthesia is on the opposite side.   The recent experimental work of Messrs. Gotch and Horsley[2] on the electro-motive conductivity of the spinal cord, favours the views of Longet and Schiff, that the posterior columns on the same side are the main afferent channels.   Their method of research undoubtedly shows the existence of unbroken tracts of fibres passing up the cord on the same side as the entering posterior nerve roots, which the degenerative method also brings into prominence, but neither method distinguishes between centripetal impressions and sensation proper.   Our experiments indicate that the tracts subserving sensation, until restitution occurs, pass up the opposite side of the spinal cord.

·   *The reflexes.*—The state of the reflexes, both superficial and deep, is of some clinical interest.

The experiments show that immediately after, and for a short time subsequently, the knee-jerk on the side of the lesion was in abeyance or very much diminished, while that

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[1] Ferrier, "Croonian Lectures," 1890, p. 95.

[2] Gotch and Horsley, "Croonian Lectures," 1891. *Phil. Trans.*, vol. 182B., pp. 267-526.

on the opposite side remained normal. Within a short time (a few days in most cases) the hitherto absent knee-jerk returned, at first sluggishly, and then of normal strength. In the first experiment, where resection of the opposite side of the cord was performed, the knee-jerks showed similar variations, absent on the side of the lesion, of apparently normal amount on the opposite side. As rigidity and contracture proceeded, both knee-jerks became exaggerated; the superficial reflexes, especially that occasioned by tickling the sole of the foot, were in all cases found to be intensely exaggerated on the side opposite the lesion, those on the same side were either in abeyance or only slightly marked. The exaggeration of these reflexes remained for some weeks, when they gradually diminished to the normal extent. In the first experiment, where a second section was made on the opposite side, similar exaggerations occurred on the side opposite to the lesion; they showed no signs of diminution, while those on the other side increased as rigidity and contracture progressed.

Vaso-motor and trophic effects.—Immediately following the operation, the temperature on the paralysed side was found to be considerably higher than on the non-paralysed. This lasted for several days, but with the return of the motor functions, the elevation of the temperature subsided. In one experiment the temperature on both sides had become equal by the twenty-fifth day.

The muscles of the paralysed limb atrophied to a small extent, the circumference of the affected limb was less, and the muscles were soft and flabby. Their reaction to electricity was not materially altered. The limb remained slightly atrophied after the return of movement. Cutaneous tropho-neuroses were observed in only one case on the side opposite the lesion.

Organic functions.—In the recorded cases of wound of the spinal cord giving rise to the symptoms and signs of a half lesion, involuntary passage of urine and fæces was noted for some days. This was never noticed in any of our experiments, although retention of urine was usually present for twenty-four hours after the operation.

In none of the experiments was any impairment of the respiration observed, not even in the high hemisections immediately after the operation.

ADDENDUM.—The following is the condition of the monkey illustrating the fifth experiment on the *thirtieth day* after the operation :—There is perception and localisation of tactile and painful impressions on the left upper and lower extremities, and the left side of the trunk. On the right upper limb the sense of touch is well marked, but the sense of pain is defective. On the right lower limb tactile and painful impressions are localised above the knee, while below the knee anæsthesia of both forms remains. There is rigidity and contracture of the paralysed extremities, while there is very little evidence of return of movement even at the left hip joint.

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